# TECHBRIEF

U.S. Department of Transportation
**Federal Highway Administration**

# Automated Machine Guidance with Use of 3D Models

CASE STUDY • SPRING 2014

COLORADO I-70 AUTOMATED MACHINE GUIDANCE

## ABSTRACT

Automated Machine Guidance, or AMG, uses data from sources such as 3D engineered models to provide real-time horizontal and vertical location information to the operator of construction equipment during earth work and paving operations. Using AMG, the equipment adjusts automatically based upon that 3D modeling information with operator override, as needed. This technical brief looks at a case study in Colorado where Colorado Department of Transportation (CDOT) used Automated Machine Guidance to complete the milling process for a concrete whitetopping project. Both the contractor and CDOT learned some valuable lessons from this initial AMG project.

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## BACKGROUND

Automated Machine Guidance (AMG) is a downstream application that can be applied to highway construction projects to provide construction efficiencies through enhanced location referencing. Using a 3D model, construction equipment is guided to improve accuracy and accelerate certain construction processes.

Three dimensional machine control and guidance systems began to appear on the market in the late 1990s. Typically such systems comprise a computer within the cab of the construction equipment that is integrated with a Global Positioning System (GPS). Accessing GPS information, the onboard computer evaluates the machine's horizontal and vertical position relative to its location in a proposed computer generated model of the project. The machine's operator is able to use information from the onboard computer to control the machine's equipment, although in recent years computer advances have made it possible for the onboard computer to link directly to the machine's operating systems, controlling its activities and movements with minimal input from the operator.

Most current applications of AMG relate to large earthwork and grading projects. Because the technology has repeatedly proven its accuracy, efficiency, and ease of use, AMG is now widely used within the civil industry, specifically in site grading and excavation for land development projects, but State DOTs have also begun to adopt the technology for road building projects in recent years.

Using AMG for roadway grading is in the early stages of implementation, and the development and testing of future applications is ongoing. Most of this development focuses on extending these concepts into other areas of construction beyond grading, such as paving and underground operations.

To assist state agencies that are considering AMG, AASHTO recently published a *Quick Reference Guide to the Implementation of Automated Machine Guidance Systems*. This study provides a valuable resource for agencies that are preparing to use this technology as the document outlines the actions required to complete all stages of the project: planning, survey, design, bidding process/contracts, and construction. It also includes sample specifications, special provisions, process descriptions, and documents from several State DOTs describing their practices for machine control, surveying, data format and transfer and related processes. The AASHTO Guide may be very valuable to an agency that is considering using AMG, as it provides examples and considerations for project selection and applying a workable process.

While some states, such as New York, Minnesota, and California, among others, have used AMG extensively enough to have developed implementation guidance documents, others, such as Colorado, have only recently begun exploring the potential for using AMG. In 2011, Colorado DOT undertook its first AMG project to remediate the poor roadway ride quality and pavement conditions on I-70 in the western portion of the state. That experience is described below.

## THE MESA COUNTY, CO I-70 REPAVING PROJECT

Over the years, paving, asphalt overlays, and expansive soil conditions caused very severe longitudinal undulations in the pavement on stretches of I-70 in Colorado, resulting in a ride so rough that drivers were unable to travel at speeds approaching the 75 mph speed limit. The infrastructure needed to be corrected, but using traditional mill and fill or mill and concrete overlay would have simply maintained the existing profile, which was not acceptable to begin with. CDOT opted for a variable depth mill and "whitetopping," or resurfacing the roadway with concrete instead of asphalt.



**Milled Segment of I-70 Reveals Asphalt Depth Variance.**

Asphalt depths on this surface varied considerably as shown in the photo, with the milled depth varying from 7 inches to zero inches in a single 100-ft stretch. This is a rural setting in which there were few "hard" elevations (project end points, weigh-in-motion pads, Port of Entry, exit/entrance ramps, and bridges) that had to be matched by the new pavement profile. All these factors contributed to making this project ideal for the application of an approach that incorporated modeling and automated machine guidance and control.

## THE PROCESS

Performing variable depth milling would have been very difficult to survey stake due to the undulating surface condition and would be extremely labor intensive.  CDOT issued plans and specifications for the project that would make it beneficial for bidders to propose using AMG. CDOT used a traditional design-bid-build procurement process for which the lowest cost qualified bid wins the contract. As a result, any bidder that proposed the AMG process had to compete directly with traditional processes.
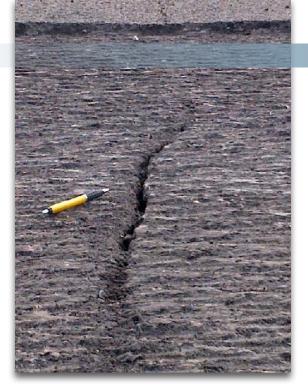
The successful (low bid) contractor on the resurfacing project was required to determine the topography for the existing roadway profile, and opted to conduct a GPS survey (see photo). The vertical element of the cartesian system (z-coordinate) is less accurate than the horizontal coordinates , however––sometimes by as much as plus or minus an inch. In a resurfacing project, if the estimated average new pavement depth is off by even a small amount, there can be a significant impact on material quantities needed and project cost. In order to decrease risk and obtain a more accurate profile, the contractor conducted five survey passes (i.e, left/right edge of soil, left/right edge of lane, centerline) at 25-foot intervals on both eastbound and westbound lanes. Although CDOT specifications required 100-foot spacing at these five locations, the contractor felt that it would be of benefit to conduct more frequent measurements.

Upon receipt of the GPS survey, CDOT used MicroStation and InRoads design automation tools to create a vertical profile model with projected milling depths to reduce the bumps and dips present in the existing profile. CDOT established the finished grade (paving) profile that would correct the extremely poor riding surface and provide for an acceptable ride for the 75 mph speed limit.



**The winning contractor conducted five passes at 25 ft intervals on both eastbound and westbound lanes for a GPS survey.**

Deeply cracked asphalt on a milled section of I-70 illustrates the poor condition of some of the existing pavement.

In a few locations leveling was required to tie in to "hard" existing paving surface elevations where milling would leave less than the 8 inches of asphalt required for the 6-inch concrete whitetopping design. The profile that CDOT established limited the full-depth paving to only these hard tie-in locations. It also reflected the agency's attempt to optimize the pavement design, balancing ride quality against excessive leveling course concrete (Furnish Concrete Pavement – Thin Whitetopping – CY).

In areas where the milling process left less than 8-inches of existing asphalt – typically where the contractor needed to tie into the existing profile at the beginning and end of the project, at weigh in motion stations, at bridges, and at on/off ramps – the full-depth paving was unavoidable. The high spots on the existing undulating roadway surface were milled in order to achieve the new profile grade.   The optimum mill depth was 2 inches, the minimum to produce a roughened surface for the whitetopping was ½ inch, and the maximum mill depth was approximately 4 inches (assuming the existing asphalt depth was 12 inches).

The contractor positioned robotic total stations to measure the surface in the X, Y and Z planes. Robotic total stations use electronic distance meters to measure the distance from the station to its target with accuracy to within a few millimeters.  Using a prism that reflects light back to the instrument from the target, the electronic distance meter determines a remote measurement that is reported through radio communication to the electronic data collector (i.e., telemetry). The use of these prisms, servomotors, and infrared technology allow the robotic total stations to search for and lock onto targets automatically.  This unique feature enables the user to easily move the station around jobsites without losing targets.

On the I-70 project, the milling machine was operated by contractor personnel, but the milling itself was controlled by the onboard computer,



Robotic Total Station

The antenna extending above the umbrella canopy on the milling machine receives wireless communication from the robotic total station. The operator controls the lateral movement of the machine, but the vertical movement is guided by AMG.  The track height adjusts automatically to meet the profile, milling to an elevation 6 inches below the finished grade.

which conducted the milling down to the mill depth that the CDOT engineer assigned for that profile, varying the depths of the cut automatically based on inputs from the robotic total station. While the machine's track height

adjusted automatically to meet the milled surface profile, the operator monitored the milling and had the ability to intervene and make adjustments should the screen reports deviate from the pre-set elevation.

The contractor was comfortable with the signal they observed from the robotic total station up to about 300 feet, so total stations were set every 600 feet so that the machine was never more than 300 feet away. The milling machine was set to cut six foot wide swaths in five or six passes.

The following describes some of the experiences of both the DOT and the contractor on the 4.5 mile repaving project and describes some of the issues that arose that they have learned from.

## LESSONS LEARNED

### UNDERSTAND THE AMG TECHNOLOGY, REQUIREMENTS, AND PROCESSES TO DEVELOP PLANS AND SPECIFICATIONS THAT GIVE MORE SPECIFIC GUIDANCE TO BIDDERS.

Both CDOT and the contractor learned many important lessons from this project. CDOT discovered that, being its first project, the agency would have benefitted from a better understanding of the AMG technology and processes in order to develop plans and specifications that would have given tighter direction to bidders.



The machine operator reads the screen, which tells him where there are deviations from the pre-set model.

For example, due to the limited construction season for paving in Colorado, the project schedule was very tight. CDOT did not have enough time in design to collect the topology survey data necessary to generate a final grade profile prior to formally requesting bids. The agency arranged the project so that the contractor would collect the topography information and generate a proposed finished grade surface for the project. This proposed surface was then approved by CDOT before being implemented. Had CDOT had more time during the design process, however, the agency would have collected its own topology survey data and provided a proposed finished grade for all the contractors to generate their bids from. This would have evened the playing field for the contractors because it would eliminate many unknowns and inconsistent bidding approaches. Known mill depths, "Furnish Concrete" quantities, etc. would have been available at bid rather than bidding the unknown.

**THE OWNER SHOULD CONDUCT A HIGHLY ACCURATE INITIAL SURVEY AND KEEP CONTROL OF THE SURVEY THROUGHOUT THE PROJECT.** As described above, if time had allowed during the design process, CDOT would have collected its own survey data and provided a proposed finished grade from which all the contractors could generate their bids. Not only was the longitudinal profile difficult to match but cross slopes and superelevation changes presented challenges for tie-ins at bridge approach slabs, exit/entrance ramps, weigh-in-motion pads, and underpasses. Due to these factors, the contractor was unable to produce the finished surface that CDOT would deem acceptable. The survey company that collected the data was unable to produce something to correct both the profile and cross slope data at the same time. The design became a partnership between CDOT and the contractor to produce a finished surface which satisfied CDOT's needs and balanced the contractor's needs for milling material and minimizing the additional "Furnish Concrete" quantities. Furthermore, a more accurate initial survey that tied in the boundaries would have been very helpful. While there were only a few set elevations that needed to be matched by the finished profile grade, it still presented a challenge for the process.

**ELIMINATE AS MANY UNKNOWNS IN THE BIDDING PROCESS AS POSSIBLE.** This lesson is also related to the need for an accurate initial survey to provide bidders with as much "known" information as possible so that they can compile a more accurate bid and develop a more cost-efficient process for conducting the project. Uncertainty in the bid process leads to higher bid prices since bidders must factor their perceived risk into bid prices. Had CDOT established the finished grade profiles as part of the bid documents, bidders' uncertainty could have been greatly reduced, which would likely have been reflected in lower bid prices and more accurate production rate and materials estimates.



In some spots there was near zero depth to mill and maintain the sub structure for the whitetopping.

The successful contractor had estimated an average milling depth for the project in order to establish a production rate for the milling process and, thus, the milling unit bid price. The contractor expressed that their estimated average milling depth of 4.5 inches was far below the actual average depth. This may have balanced out due to many locations requiring no milling at all, thus improving production rates. Additionally, the millings from the milling process saved the contractor money because CDOT allowed the contractor to use the millings as shouldering material and the contractor used the millings to produce a tracking pad for their paving machine. Had they not produced these millings, they would have had to haul ABC class 7 to the jobsite, therefore adding more to their expenses.

Because of the miscalculation in the average milling depth, other elements of the contractor's efforts were also impacted. The pay item "Removal of Asphalt (Planing)" for milling is set in square yards, with the CDOT estimate shown on the construction bid documents. Each bidder must estimate the milling production rate based upon the depth of milling. On a typical mill and fill project, the milling depth is fairly consistent. Because the contractor found that their estimated average milling depth was greater than the anticipated average depth, the production rate for the milling operation was also affected. The subcontractor expressed their preference for having the removal of Asphalt Mat (planing) pay item paid in square yards per inch to

compensate for the variable mill depth throughout the project. CDOT felt that this would have been covered had the subcontractor been able to estimate the work according to a proposed final surface during the bidding process.

Finally, the contractor expressed that, for this milling operation, designed to correct the existing unacceptable undulations in the longitudinal profile, the specified 8 percent allowable concrete quantity overrun was far too tight. However, a "bust" in the contractor's survey on the westbound lanes also contributed significantly to the quantity overrun. This was only discovered after the string line was put up and the contractor observed that the space between the "milled" surface and the final surface was greater than 6 inches. The capability of the initial GPS survey to capture the vertical profile accurately was questioned as this measurement can vary by up to an inch, which is a significant quantity for this project's 6-inch concrete overlay.

## QUALITATIVE ASSESSMENT OF EFFICIENCY GAINS USING AMG FOR MILLING

Caterpillar conducted a study and field test of Machine Control AccuGrade systems at its facility in Spain in 2006. The resulting report is titled the *Road Construction Production Study*. The project time and labor savings involved in surveying for the AMG milling operation of the CDOT project would be fairly similar to those experienced on the fine grading for the Caterpillar field test. With conventional construction, the profile grade and cross-sections from that grade would have to be staked by the contractor, perhaps as frequently as every 25 feet in order to reproduce the accuracy of the AMG methodology.

The 2006 Caterpillar study found a **95 percent** reduction in surveying labor for the overall roadway construction test. Production rates for the milling machinery and operators would also be expected to experience significant efficiencies using AMG. Consider that with conventional methods the operator must manually adjust milling depths, reacting to the surveyed cross-section points. Since the AMG operation continually and automatically adjusts milling depths relayed by the robotic total stations, the operator does not need to slow to manually check against survey points. So from the 2006 study it demonstrated a **101 percent** productivity gain using machine AMG. This saving was based on one subgrade layer and one base course layer; road construction involving more layers would be expected to garner additional time savings.

*AASHTO Subcommittee on Construction, Quick Reference Guide to the Implementation of Automated Machine Guidance Systems, n.d. Available at:*
http://construction.transportation.org/Documents/Technology%20and%20Computers/QRG%20AMG-Final.pdf

*Caterpillar, Road Construction Production Study, December 2006. Available at:*
http://www.trimble-productivity.com/media/pdf/ProductivityReportCATRoadConstruction2006.pdf

*Minnesota Department of Transportation, Best Practices – Machine Control Evaluation, May 15, 2007. Available at:*
http://tig.transportation.org/Documents/BestPractices-MachineControlEvaluation_FinalReport(MnDOT).pdf

*Taylor, D., Machine Guidance for Highway Construction, Presented at the North Carolina Department of Transportation's Construction Engineers Conference, March 2006.*

*University of Wisconsin – Madison, Implementation of GPS Highway Construction Equipment, April 2007. Available at:*
http://cmsc.engr.wisc.edu/Vonderohe2007Apr01.pdf

*Wisconsin Department of Transportation, RD&T Synthesis Report: GPS in Construction Staking, 2006.* Available at:
http://wisdotresearch.wi.gov/wp-content/uploads/tsrgpsstaking1.pdf

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